Longevity Planning, A Cost Reduction Strategy for Ground Systems of Long Duration Space Missions

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Abstract

This paper explores the Longevity Planning efforts for New Horizons mission to Pluto, currently in the design phase with a planned launch in 2006. New Horizons could begin returning Pluto Encounter data in 2016 and could continue exploring the outer reaches of the solar system beyond 2020.

Introduction

Maintainability is defined in NASA Handbook 5300.4(1E), "Maintainability Program Requirements for Space Systems" as: "A measure of the ease and rapidity with which a system or equipment can be restored to operational status following a failure"[1]. The issue of sustaining maintainability of a ground system over a decade-long mission could represent significant cost in the later days of operations. In missions with a long cruise phase before the actual encounter, the ground system is required to operate with full functionality after an extended hibernation in the hostile environment of normal everyday life on Earth. Planning for access to spare parts for decade-old computers, software compatibility with future operating systems, and transition of knowledge from key individuals are some of the issues in planning for the longevity of a ground system for such missions.

This process of "maintaining the maintainability" and planning for it is considered Longevity Planning. The process is best understood by stepping into the shoes of a subsystem designer and asking the following set of questions:

> In 10 years, when I'm called out of retirement to fix this system, what will I wish I had saved?
>
> Who will I need access to?
>
> What equipment will I wish I still had?
>
> Will I still be able to refer back to my design notes?
>
> And where will I find the parts, soldering stations, software development tools, etc?

Another example of the issue facing the Longevity Planner works like this: Think back to the first computer you ever used productively—now imagine that there is some key piece of information or program stored inside it that you simply must recover, and ask yourself the following:

> Where is the machine, the manual, spare parts?
>
> What media were used for storage and is any of it still readable, on what devices, and do any of them still work?
>
> And perhaps most of all, "Where's Bill now? He always knew just what to do when I couldn't get the darn thing to behave right!"

If you had known back then that you'd need that information/software to be operational today, what would you have done to guarantee its ongoing availability?

Searching online for relevant information shows little evidence of much concern for, or understanding of the need for Longevity Planning in the spacecraft mission operations world. The overall tendency seems be to deal with the unavailability of knowledgeable staff and spare parts for obsolete components on an *ad hoc* basis. This lack of planning and the belief that "maintenance of a system is not an issue for the design team" has lead to increased cost and decreasing system reliability in numerous situations. It is exactly this lack of Longevity Planning that has left NASA searching eBay for surplus 8086 processor-based systems in order to maintain key subsystems of the Space Shuttle Ground System[2].

Web searching for maintainability yields no shortage of information on maintainability or on software to perform maintainability analysis. But none of the information relates to the need to **plan** for repairing or replacing failed obsolete components, preserving the knowledge base of a system to facilitate its future repair, redesign or

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replacement, or assuring the availability of software or custom hardware in the event the vendor becomes defunct. Rather, the focus is on analyzing failure rates, determining Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR) statistics. While these statistics are frequently utilized in the design process to determine the "maintainability" of the system, little or no effort is invested during the design phase to address "maintaining the maintainability" of systems.

Planning for Longevity

For the purpose of this paper, two top-level paths were considered and evaluated. Each path has significant advantages and disadvantages.

The first path considered was to routinely upgrade any system that was not compatible with the latest hardware platform. These upgrades would be scheduled to occur throughout the mission at intervals of three to five years. The advantage of this approach is that all computers would be covered under a manufacturer's extended warranty. This cost was more easily quantified and could be budgeted throughout the mission life without incurring additional cost early on. The disadvantage of this approach became evident when considering the need to port custom software and unsupported versions of commercial software into a new operating environment. This approach seemed to require regular rewrites of substantial software components for the ground-based system. Further, this approach did not take into account the need to maintain custom hardware such as the Spacecraft Simulator.

The second path considered was to essentially freeze the entire ground environment prior to launch and apply resources to maintain that generation of hardware in an operational condition for the life of the mission. While this may seem entirely impractical at first glance, one mission being flown at APL has successfully implemented this strategy and is now approaching 10 years of successful operation of the ground system. Considering that this ground system was designed in the late eighties and remains operational and fully functional 15 years after being designed, this approach seems much less risky and more quantifiable than the alternative path.

That this ground system remains operational to this level of longevity without having planned for it further strengthens the argument supporting this path. By planning to maintain a known set of hardware early in the mission it should be possible to better assure the continued functionality of the ground based system substantially longer and meet the extended mission plan for most deep space missions.

One disadvantage of this approach is that eventually it may nevertheless become necessary to upgrade components to more modern technology. Another disadvantage is the difficulty of locating spare parts for aging electronic devices. Both of these difficulties can be largely mitigated through appropriate archiving of information and components.

The longevity-planning concept presented in this paper is derived from a number of experiences, both professional and avocational. One significant experience has been the continued maintenance and operation of a 40-year-old Ground Station asset located on the campus of the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland[3]. This 60-foot antenna system is presently operating at better than 97% success for LEO passes supporting the TIMED mission. Many of the experiences encountered in the upgrade of this asset to full CCSDS capability and maintaining the system to mission reliability standards based on 40-year-old documentation have been included in this plan. Lessons learned form the challenges of locating serviceable replacement parts and the level of documentation on the "as-built" parts needed to validate the new parts for this antenna also feed into this plan. Further, substantial personal experience repairing and restoring multi-decade-old electronic equipment has provided a unique and significant perspective on the problem[4].

This plan will detail strategies, considerations and recommendations aimed at capturing information and documentation sufficient to assure the longevity of the ground based components of long duration missions. All information and documentation should be maintained in a Technology Archive facility, along with sufficient spare parts as determined appropriate for each subsystem design team.

Plan Structure

The process of Longevity Planning breaks down into several phases, which are distributed across the mission lifetime. These phases, described in detail later, include Identification, Evaluation, Preparation, Documentation, Archiving, Assessment, Mitigation and Migration.

Identification

To be effective at planning for the continued functionality of a Ground System, including any Spacecraft Simulator that may become part of the Ground System, it is necessary to develop an accurate inventory of items, by category that will be maintained. Once an inventory is completed, key items needing special attention can be identified, the criticality of each item is assessed and sparing needs can be established. This first phase requires each subsystem team to document items within their area of expertise that could represent longevity issues along with an initial assessment of that item's criticality. This is accomplished by requiring each subsystem team to complete a Longevity Planning Questionnaire.

As a minimum, the questionnaire should collect the following information:

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- Any items needed to support programmable components that may require reprogramming during the mission to maintain functionality of each subsystem or the simulator. The make and model number of the programming device, along with any adapters needed to properly program the logic device should be identified. Any operating system or hardware platform dependencies should also be included.

- A list of any software (in-house code, custom code or purchased code) that will be required to maintain, troubleshoot or validate the subsystem during the mission. Include in this list any development software for assembling software for embedded processors and programmable logic devices. Specify any operating system or hardware platform dependencies.

- Identify any on-board batteries or battery backed-up devices (Dallas clock chips, state backup batteries, etc.)

- Identify any special test fixtures or debugging hardware needed to assist in fault analysis or stimulation and verification of the delivered components. This should include test harnesses, breakout boxes/cables, loop back/dummy connectors, stimulators and displays.

Additionally, the questionnaire is a convenient vehicle for collecting information on staff. Other members of the design team often retain unique information on obscure aspects of the system. The questionnaire should list anyone who contributed in a significant way to the subsystem design or testing. These people may have been junior members of the team but could be the only ones available in the latest years of the mission.

Evaluation

Each item captured during the identification phase above should be classified according to the significance of its availability to the mission. Items with the most critical need will have a higher priority within the Longevity Planning process.

Classes of systems:

1: Critical to normal operations – must be working continually

2: Critical to upgrades/rewrites/reaction to system loss – must be restorable to working condition.

3: No time criticality – functionality must be reproducible eventually.

The final classification for each item should be conducted at the Mission System Engineer level. Inputs from Mission Operations, Planning, Science and budget considerations should be integrated into this final classification.

Preparation

Once items have been identified and an evaluation of each item has been performed, the preparation phase begins. This phase of the Longevity Plan is focused largely on preparing the archive

Inventory

A detailed inventory of items requiring archiving should be maintained in multiple formats, including paper. The inventory should be accessible via electronic methods (web, network drive) and should be searchable by keyword. The inventory should list all items available by subsystem along with the criticality rating for the item, all contact information, spares depth, and date of last action.

Documentation

Along with all routinely deliverable documentation required of each subsystem team, the longevity requirements on long duration programs cannot be satisfactorily met without several additional documentation efforts. These additional documentation requirements provide the ability to capture information during the later design and early operations phase of the mission. Capturing design and operation data at this interim point in the mission could prove essential for longevity efforts later in the mission.

Subsystem Design Document

Each subsystem design team should provide a section in the Subsystem Design Document devoted to Longevity Planning. In this section, the subsystem designers should identify items of specific longevity concern (those items listed in the Subsystem Longevity Planning Questionnaire). Further, the Longevity Planning section should address, as a minimum, the following for each item listed:

? Failure indications

? Troubleshooting tips and techniques

? Method of repair

? Additional sources for spare parts

Subsystem Detailed Longevity Plan

As an alternative to providing a section in the Subsystem Design Document addressing longevity planning, the subsystem designers may elect to provide a separate document dedicated to Longevity Planning. This document should include all information required to assure the continued functioning of the subsystem for the duration of the mission.

By choosing to deliver a Detailed Longevity Plan, the subsystem designer affords significantly more detail on maintaining the subsystem components in exchange for a

delayed delivery of the document. The Detailed Longevity Plan should be released within 60 days after launch.

Capabilities Document

In order to effectively mitigate any issues of obsolescence in the future, a clear and well-documented description of the available functionality is also required for each subsystem. While some may feel the design requirements are adequate for this purpose, history and experience has shown that design requirements alone are inadequate to replicate a completely functional system. In many cases, particularly using heritage designs, capabilities are included that exceed those of the requirements, since removing them would destroy the heritage of the design. This excess capability creates an opportunity for undocumented features to be relied on by higher-level systems as the mission proceeds. This can be a significant issue on long duration missions as science teams have extended periods of time to discover novel ways to improve science data returns by using these excess capabilities, thereby elevating them to requirements—in a longevity planning context.

Unlike a Requirements document, which is written to define the minimum capability needed prior to commencing a design effort, a Capabilities Document is written after the completion of the design and is intended to document the complete capability of a subsystem. A well-written capability document will include any feature or function of the subsystem and all information needed to utilize it, interface with it, debug it and duplicate it. The Subsystem Capabilities Document should be written from the outside looking in and be independent of the higher-level environment. This perspective is significant in that it allows the potential for creating the same capability in a new, not yet anticipated environment. This would be essential if it became necessary to emulate the functionality of the subsystem as a software simulation a decade after the design team finished.

Delivery of the Subsystem Capabilities Document should be required not later than 60 days after launch.

Engineering Notebooks

The process of generating released documentation usually involves the distillation of information contained in the engineer's notebooks into a more cohesive and concise form. While these released documents are normally considered sufficient and even preferable for documenting the workings of a subsystem, the process of generating them can lead to loss of subtle characteristics of the subsystem. Access to the information contained in the designer's engineering notebook could prove to be the key element in solving some subtle issue precipitated by repair or replacement of an adjacent subsystem. Each subsystem team should contribute copies of all relevant engineering notebook contents to the Technology Archive.

Procedures and Scripts

During the routine development, testing, integration and operation of each subsystem, various test scripts and procedures are generated. Archiving these items is an important part of assuring access to historical baselines and providing the ability to verify future performance relative to subsystem history.

All test scripts and procedures for each subsystem should be maintained as part of the archived information of the mission. Special care must be exercised to assure the continued availability of these scripts and procedures while ensuring that they cannot be unintentionally used during routine mission operations.

Electronic Media

Electronic media, by its very nature is transient. Data stored on networks is prone to being moved, deleted, and modified as well as lost due to failure of the magnetic medium on which it resides. Regularly scheduled backups mitigate much of this but still rely on magnetic or optical storage to be effective. Magnetic recording media is erasable and prone to accidental overwriting as well as degradation due to the effects of the environment in which it is stored. Optical storage devices such as writeable CD ROMs mitigate some of the deficiencies of magnetic storage, but are not a permanent storage medium. CD ROMs will degrade over time and need to be refreshed every 3 to 5 years to retain data quality. A regularly scheduled upgrade to new data storage media will also be required.

Multiple formats

The issue of compatibility of data formats over multi-year periods is another area of concern for Longevity Planning. The issue is that as software applications advance, new features are added which result in the need to alter data storage structures for the application. In some instances, commercial software has lost the ability to read formats three to five generations old. In the case of popular software applications, new versions appear on an annual basis. This could mean that a document written in the dominant word processor of today is not readable after upgrading to a new version of the same word processor five years from now. This situation may also present a significant issue for electrical and mechanical design documents as well as graphic files.

To guard against electronic copies of documentation becoming unreadable, all documents should be kept in multiple formats. This could include paper, flat ASCII (for word processor documents), comma separated variable format (for spreadsheets and databases) as well as the native format of the application, or other compatible applications. Graphic files (such as GIF & JPG files)

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should be saved in several formats including the relatively new PNG format.

Periodic audits of the electronic archive should be conducted and data should be ported to new formats as they become available

Archiving

Perhaps the most visible component of Longevity Planning, and the one most associated with information is the archive. Sometimes thought of as the simply a library for copies of old data books, the archival process is not limited to paper in the context of longevity planning. Long duration space missions should maintain a Technology Archive of all items needed to meet the longevity needs of the mission.

Technology Archive

The Technology Archive should not be limited to paper volumes, but should include all manner of data and hardware needed to support the longevity requirements of the mission. The Technology Archive should include copies of all review documentation, design documentation, Capability Document and Detailed Longevity Document on each subsystem in multiple formats. These documents should be maintained in original format and be regularly updated to "current format" so as to be accessible to those operating current technology equipment in "the real world".

Machine-readable information is dependent upon a compatible machine to permit its reading. In congruence with this axiom, and given the predictable and increasingly accelerating obsolescence of information technology machinery, the National Archives and Records Administration (NARA) prescribes specific policy for the preservation of federal and public electronic records. Preservation requirements entail timely and periodic alterations to the digital format of the records, including rewriting stored data to new physical media, and maybe changing the way the records are digitally encoded from an obsolescent to a persistent format[5]. Digitally encoded operating systems and software to drive data processing hardware are just as much an electronic record as the data content produced and manipulated by the systems, and are therefore subject to the same preservation policy.

All spare hardware should be inventoried in the Technology Archive and many of the actual components should be maintained in a part of the facility designated for their storage.

Some spare components should be maintained in alternate facilities due to special requirements for geographic diversity or the need for a more controlled environment (such as a flight certified stockroom). These parts should also be listed in the Technology Archive along with specifics on their location and availability.

Residual sparing

During the past few years several ongoing operations within the space community have employed a new method to obtain additional spare components for aging ground systems. The process involves finding needed components that are being eliminated from use by other missions, programs, or organizations and ingesting these residual items to augment the spares inventory. This method of increasing the "spares depth" of the archive can be a significant cost savings to the program once the functionality of the components is verified. This concept is referred to in this paper as residual sparing.

The residual sparing concept has recently been expanded by NASA to include searches of the World Wide Web for various computer systems needed to support Shuttle operations. The concept should also be applied within an organization by assuming ownership of components shed by other programs to use as spare hardware for the long duration program.

Procedures should be established to capture any surplus equipment generated by other departments that could benefit the longevity needs of the long duration program.

Long duration flight spares inventory

Special attention is required to assure the continued availability of components not stored in the Technology Archive. New procedures or modification of existing procedures used by any flight stockroom or other facility may be required to assure that no components usable to long duration mission are purged from the stockroom without first being cleared by the program office and the Technology Archive. This requirement should apply to any parts useable by the long duration mission even if the parts were purchased to support another program. Parts usable by the long duration program should be retained for the duration of the program.

Transfer of spares stock from other missions.

In the event that hardware purchased to support other missions becomes excess property of that program, the long duration mission should be granted "right of first refusal" on any property that could support the longevity needs of the program. This excess property should be transferred to long duration mission and maintained by the Technology Archive until deemed excess or surplus.

Software products

Installable copies of all purchased software items should be maintained in the Technology Archive. Any items that are used to support any aspect of the program should be available in the Archive. Individual groups using special software in the routine development of their subsystems (i.e. used across multiple programs) should deliver backup copies of the operational software to the Archive until that

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software is replaced by a more current version. At that time, the original installable copy of the software along with all documentation needed to install and operate the software should be delivered to the Technology Archive.

Assessment

The long duration mission should conduct ongoing assessment of all items covered under the Longevity Plan to identify items that may be nearing the end of operational life. Further, as a part of this assessment activity, the program should attempt to identify items that may be becoming unavailable and should be acquired in quantity prior to total obsolescence.

Assessment should be conducted as a routine part of any annual, or routinely scheduled checkout planned by Mission Operations.

Ground System and simulator components and support systems should be operated and/or analyzed to determine their operability and depth of spare component availability. Items deemed to be non-operating or to be operating below established performance specifications should be repaired or replaced with spare items from the Technology Archive.

During the assessment period, spare items held in the Technology Archive should also be evaluated. The evaluation will not be limited to assessing performance or the condition of the item, but should also include assessing the need for, and availability of additional items from other sources.

Items that are becoming increasingly difficult to obtain or items with an increasing failure rate may require special attention.

Mitigation

This phase of the longevity plan focuses on efforts to repair of restore a component of the Ground System to proper functioning after a failure is detected.

Fault analysis

From the Longevity Planning perspective, fault analysis is another opportunity to collect data and revalidate procedures that may be years old and may not have been used by the currently available personnel. The Technology Archive should provide all relevant information and assist in the fault analysis effort as requested. A significant part of the fault analysis process should focus on generating a documented trail describing the symptoms of the failure, the procedures and tests conducted and the results obtained. All information resulting from the analysis effort should be delivered to the Technology Archive at the conclusion of the repair.

Repair

The Technology Archive should provide all necessary parts, documents, software and tooling as required, to facilitate

successful repair of the failed item. Additional technical support, repair facilities and skilled labor can be sourced form other areas. Any additional resources required but not available in the Archive will be documented for future archiving.

Validation

Following the repair, validation tests should be performed to assure the proper functioning of the repaired subsystem and the adjacent subsystems. This testing should rely on test scripts and performance information provided by the Technology Archive. Any tests, procedures or information needed but not available through the Archive should be documented and included in the archival update.

Spares status

Following the removal of any faulty component, the Archive should endeavor to replenish spare stock with another part or to coordinate repair of the defective component.

Archive update

Following any mitigation effort, a complete update of all archival items related to the effort should occur. The intent is to enhance the quality and accuracy of the archive in an iterative process.

Migration

At some point, in spite of extensive effort to maintain existing technology, it may no longer be possible to maintain the functionality of a system at an acceptable level of reliability. Part of Longevity Planning establishes a set of criteria for the migration to new technology in order to preserve functionality.

The best time for a migration to occur is while the existing system is still functioning at an acceptable level. This gives the migration team an opportunity to validate the performance of the new system by comparison against the performance of the existing system. Migration to new technology should begin when a system spare parts inventory is reduced to the "one deep" level. Waiting until the last spare is installed (zero deep on spares) may not allow sufficient time for development and testing prior to complete system failure.

Methodology

The process of migrating any subsystem to a new technology or new platform is the most tedious and problematic process conceivable for an operational Spacecraft Ground System. The details of that process for any single subsystem are far too involved to adequately cover in this plan. Moreover, the details will vary from subsystem to subsystem. Even more significantly, the low fidelity of the technological prognostication available prevents the development of any significantly detailed

procedure. As a result, it is only possible to define a general methodology for a migration, the details of which must be left to develop over time.

Some considerations for acceptable methods of implementing new systems include the following:

1: Hardware compatibility with original platform and media

2: Software Emulation of

    a: Original hardware (media compatible)

    b: Original media (i.e., disk/tape images on larger storage device)

3: Upgrade underlying software (requires regression testing)

4: Rewrite functionality into new software (requires regression testing)

Regression testing

Every subsystem listed and assigned a level of criticality should provide a test procedure or similar means of checking out the complete functionality of the subsystem (as defined in the Capabilities Document). Depending on the criticality of that system, such a test should be repeated at periodic intervals (for hardware) and at every underlying hardware platform change (for software).

Archive update

Following any migration effort, a complete update of all archival items related to the effort should be conducted. The intent is to enhance the quality and accuracy of the archive in an iterative process and to maintain the ability to assure continued longevity of the new system.

Conclusion

This paper presents the concept of Longevity Planning as a potential cost savings for ground systems used by long duration space missions. Quantifying actual cost savings is not possible except by comparison against the alternative, recurring hardware upgrades and the resulting software rewrites that could represent significant costs in later years. The plan presented in this paper is intended as an overview of the basic issues that should be considered, the specifics in particular areas are to be addressed at lower levels within the design team—rely on those in the trenches to better see the worms.

Acknowledgments

References

[1] http://llis.nasa.gov/llis/cgi-plls/plls_lesson?num=0835

[2] "Space Shuttle Officials Search High And Low for Vintage Spare Parts", Space News, April 29, 2002

[3] http://www.scf.jhuapl.edu

[4] Gemeny, S. E. and Gemeny, M. W., "Ground System Planning for Long Duration Space Missions helped by Lessons Learned Resurrecting Obsolete Computers", 5th International Symposium on Reducing the Cost of Spacecraft Ground Systems and Operations (RCSGSO) 2003

[5] Electronic Records Archives Requirements Document (RD), Section 2.7.2 – Preservation http://www.archives.gov/electronic_records_archives/about_era/requirements.html